THE MARS SUNPHOTOMETER PROJECT

Strawa, A. W.(1), Velante, M. B.(2), Papadopoulos, P.(2), Colaprete, A.(1)

(1) NASA Ames Research Center, MS 245-4, Moffett Field, California, USA, 94035-1000, astrawa@mail.arc.nasa.gov, tony@freeze.arc.nasa.gov

(2) *San Jose State University, Department of Mechanical and Aerospace Engineering, One Washington Square, San Jose, California, USA, 95192-0087,* mvelante@email.sjsu.edu, ppapado1@email.sjsu.edu

ABSTRACT

The interaction between the sun's energy and Martian dust is now recognized as one of the biggest driving forces for climate on Mars, yet little is known about the physical and optical properties of this dust or its spatial and temporal variation. Recognizing this, we are proposing the development of an instrument concept that would be able to provide more valuable information about Martian dust than has been possible in the past. The instrument is based on the sunphotometer concept, however it would have no moving parts. Consequently, it would be small, light weight, and consume little electrical power.

The Mars Sunphotometer Project (MSP) is a joint NASA Ames Research Center (ARC)/San Jose State University (SJSU) initiative to investigate feasibility of a robust remote sensing package design for the Martian atmosphere.

The goal for this 2-year project is concept validation through development a computer model of the instrument and fabrication of an Earth based prototype for testing at San Jose State University.

1. BACKGROUND

The interaction between the sun's energy and Martian dust is now recognized as one of the biggest driving forces for climate on Mars, yet little is known about the physical and optical properties of this dust or its spatial and temporal variation. Dust is a ubiquitous component of the Mars atmosphere with concentrations that vary seasonally and annually [1]. The size of Mars dust storms vary from dust devils to planetary scale storms, which affect the atmospheres thermal and dynamic structure [2,3]. During 2001, a major Mars global scale dust storm occurred and was observed by the Thermal Emission Spectrometer (TES) on the Global Surveyor satellite and by the Space Telescope (among other instruments). Due to the strong absorption features of Martian dust, it is typically the major absorber in the Mars atmosphere. This absorption of solar radiation controls the heating profile in the Mars atmosphere and therefore affects the synoptic scale circulations [4]. The Mars Exploration Rovers (MER) have been instrumental in the study of seasonal dust behavior [5].

In addition to affecting the thermal properties of the Mars atmosphere, the dust also creates problems for remote sensing efforts. Spectral infrared (IR) measurements are routinely used to infer chemical composition on the Mars surface. Various sensors on different satellites such as the Infrared Imaging Spectrometer (IRIS), the Infrared Thermal Mapper (IRTM), the Thermal Emission Spectrometer (TES) and the Thermal Emission Imaging Spectrometer (THEMIS) have been used for this purpose. The presence of Mars dust affects these retrievals by absorption, scattering and emission in these wavelength regions [7].

Surface observations of Mars atmosphere have the advantage that interference from the ground signal is minimal, it is possible to make continuous long-term observations from a location, and they can verify satellite observations. Past studies of Mars dust and atmosphere from surface have largely been carried out by instruments designed for geological [7] and engineering [8] purposes and time allotted for atmospheric observations has been limited. The importance of climate phenomena, such as dust storms, and dust devils to future exploration missions require a dedicated atmospheric instrument. An instrument dedicated to Mars atmospheric study will need to be small, light weight, have low power consumption, contain no moving parts, and be capable of long-term measurements. It will be desirable for such an instrument to be capable of deployment on several different platforms, stationary, rovers, and airborne to completely characterize the Mars climate. The Advanced Sunphotometer, developed at Ames Research Center, has no moving parts and meets the requirements of size, weight, and power. It has the capability of supplying the following data products: the partitioning of direct and diffuse solar radiation, aerosol optical depth as a function of wavelength, aerosol physical and optical properties (size distribution etc. derived from wavelength dependent optical depth), particulate phase function, column optical depth of some gas phase constituents, and climatology of clouds and dust devils. This instrument is well suited for a Mars exploration mission however some aspects of the instrument and analysis methodologies need to be tailored to the Mars mission.

2. PROJECT MANAGEMENT

2.1 Collaborative Framework

The instrument development effort depends upon collaboration between ARC and SJSU and the following describes the operation of this arrangement.

2.1.1 Advisors and Team Management

The principal investigator, Dr. Anthony Strawa, developed this advanced sunphotometer concept during his career at NASA ARC. SJSU's contribution exists via Dr. Periklis Papadopoulos and his students from the Mechanical and Aerospace Engineering (MAE) department.

With Dr. Strawa as the industry advisor and Dr. Papadopoulos as the academic advisor, a graduate student/system engineer leads a team of voluntary graduate and undergraduate students. The team is divided into sub-systems and with one individual assigned as the lead, reporting directly to the system engineer.

2.1.2 Student Involvement

Over the past decade, SJSU's MAE department has produced many successful Aerospace Engineering graduates, in the field of space system engineering. Spacecraft systems design, development, integration and testing. The system engineer, Matthew Velante, BSAE, is experienced in space systems engineering on multiple levels from various projects: Spartnik team member, CubeSat system engineer, American Institute of Aeronautics and Astronautics SJSU Chapter President and Rocket Engine Design team member.

To apply the facets of engineering project management the system engineer/team leader interviews, evaluates and assigns positions to each team member based upon their level of education, experience (academic or work) and level of involvement in projects.

New team members are given assignments/tasks that enable them to apply classroom theory to a real world project.

Junior team members have broader tasks that place newer team members under their supervision. The system engineer provides guidance and feedback regarding progress in leading their team/sub-system.

Senior team members work directly with faculty and industry mentors on their specific tasks both on-campus in the field to facilitate the development of professional work related experience.

2.1.3 Task Scheduling

Along with tasks, a time schedule is set for the work to be done. System level tasks are given milestone dates for completion.

Weekly meetings are held to update progress/status on current work and possibility of completion by due date. If it has been deemed that the work cannot be completed on time, the issue is discussed as a group and the schedule is revised.

Below is the main Project Timeline, a very simplified version of the actual task schedule, but is used to observe and evaluate progress for system level tasks.

Table. 1. Project Timeline

Tasks	Fall 2004	Spring 2005	Fall 2004	Spring 2006
Platform Applications				
Sensor Design				
Optics				
Scattering Device				
CCD				
Integration				
System Bus				
Structure				
Power				
Thermal				
Payload				
Optics				
Scattering Device				
CCD				
System Engineering				
PDR				
CDR				
FDR				

New and junior team members are given tasks that can be rotated. The concept is to give them experience in various areas of the design process, both theoretical and hands on.

To facilitate clear lines of communication an Internet Newsgroup was created to enable every team member access to Team Information, coordinate tasks, access/reference documentation, and to setup conference meetings.

The following displays the basic arrangement of the team structure noting the general flow of communication and tasks.

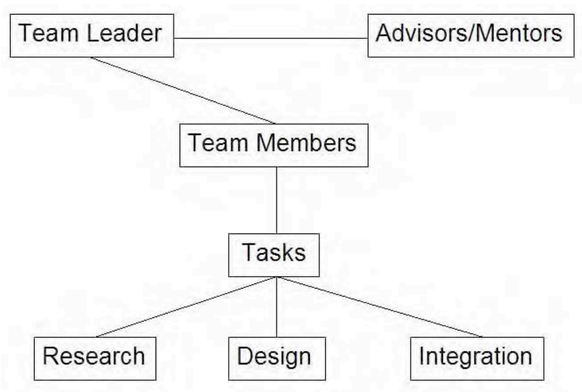

Fig. 1. Team Structure

2.2 Laboratory and Field Work

To give each team member a basic background on the project, they are taught the different components of the laboratory setup, how to assemble it and perform instrument calibration.

The instrument is also tested in the field, usually on the roof top of the SJSU's Engineering Building or NASA-Ames' Atmospheric Physics Branch. These locations provide the least solar obstructions from surrounding structures both artificial and natural.

3. MARS SUNPHOTOMETER

3.1 Sunphotometry

Sunphotometers are commonly used on the Earth's surface, as well as on aircraft, to determine the solar energy attenuated by gases and aerosol particles in the atmosphere. This information is used to determine several properties of the atmosphere including: the column abundances of gases, the spatial and temporal distribution of aerosols, and the distribution of particle sizes. A sunphotometer measures the optical depth through application of the Lambert-Beer-Bouguer Law

$$V(\lambda) = V_0(\lambda)\exp[-\tau(\lambda)m(\theta)] \qquad (1)$$

where V and V_0 are the responses of the instrument at the surface and at the top of the atmosphere, respectively; _ is the total column optical depth due to scattering and absorption; and m is the air mass traversed by the direct solar beam which, in approximation, equals 1/cos _ (_ is the solar zenith angle). Sunphotometry has been widely used for ground-based determination of the optical depth (turbidity) of the earth's atmosphere since the work of [9] over 40 years ago (see e.g., [10]. Typically, sun photometers have narrow fields of view and track the sun allowing the direct solar beam to illuminate detectors through narrowband filters [11,12]. A tracking sunphotometer has been developed for use on aircraft [13]. Another technique uses a rotating arm to block the sun [14,15]. When the rotating arm is out of the field of view, the total flux can be measured and when the arm is blocking the sun, the diffuse flux is measured, that is the solar light scattered by the atmosphere. The direct beam is the difference between the total and the diffuse. Spectral measurements of the direct beam are used to determine column abundance of gases [16,17,18] and retrieve aerosol column abundance and size distribution [19].

Table. 2. Advantages/Disadvantages of Sunphotometers

Type	Automated Sun Tracking	Hand-Held	MSP
Size	Large (decameter range)	Small (centimeter range)	Small (centimeter range)
Weight	Tens of kilograms	Less than kilogram	Less than kilogram
Complexity Mechanical	High (tracking system)	Low (using human observation)	Low (solar collection optics)
Complexity Electronic	High	Medium	High
Accuracy	High (motorized control)	Low (human error can be significant)	High (solar collection optics)
Interplanetary Mission	No (size/ weight)	No (accuracy)	Yes (light, simple)

3.2 System Overview

Unfortunately, many of the details of this instrument cannot be disclosed at this time pending patent protection.

Current sunphotometer technology requires methods of sun tracking, manual or electronic, or sun shadowing. Both methods require a costly, weight restrictive, motorized setup. The MSP simplifies a sunphotometer to an electronic device, removing the complexity of moving parts in mechanical systems. This sensor simplifies mechanical design by replacing sun tracking with sunlight collection onto a photosensitive array (typically a complementary metal-oxide semiconductor (CMOS), charge-coupled device (CCD) or a charge-induction device (CID) array) to make the instrument much smaller, compact, and reliable. Data products are downwelling flux, the direct-diffuse flux ratio, aerosol optical depth at multiple-wavelengths, cloud statistics, and an estimate of particle size. These measurements can be used to obtain an estimate of aerosol size distribution

4. CURRENT STATUS OF PROJECT

4.1 Prototype

A prototype of the Advanced Sunphotometer has been fabricated using is Vitana PixeLink PL-A653 monochrome CCD array with 1.3 mega-pixels and 8-bit resolution. Overall dimensions of the instrument are 10 cm by 10 cm by 7 cm. The array is connected to a laptop computer via Firewire for data acquisition.

4.2 Solar Collection Device Simulation Software

A computer model of the instrument has been constructed to provide a theoretical mapping from position on the CCD to a position in the sky. This simulation will be used to size and integrate instrument components in an efficient way. The simulation program also allows us to predict instrument performance and can be compared with lab calibration and actual measurements made on the roof of SJSU Engineering Building.

Coding for the solar collection device simulation software (SCDS) is now operational. Data collected in the laboratory and in the field now has a basis for comparison (actual versus theoretical). System parameters can entered into a graphical user interface (GUI) and updates the code for the specific application.

A plot showing the theoretical prediction of the array image when the source is directly overhead is shown in Fig. 2.

4.3 Detector Determination

Using various detector characteristics such as quantum efficiency, dynamic range, well depth, etc. combined with system driving parameters such as detector size and weight, a program for detector determination is being developed.

The goal is to give a projected list of options for detector selection combined with options such as anti-blooming and pixel binning.

System drivers such as complexity, integration ability (hardware and software), weight, power requirements are also evaluated for feasibility into design.

The next table display basic calculations for the received photon count for the following detectors from Apogee Instruments.

Tab. 3. Number of Photons per second received by particular detector

	$\lambda_{typical}$		
	$P_{total, min}$	$P_{total, avg}$	$P_{total, max}$
AP4	29498.2642	30641.434	32008.7547
AP6/AP6E	209765.434	217894.642	227617.811
AP8	209765.434	217894.642	227617.811
AP9/AP9E	29498.2642	30641.434	32008.7547
AP10	71378.5157	74144.7044	77453.283
AP16	29498.2642	30641.434	32008.7547

4.4 Blooming

Blooming, pixel saturation resulting in image smearing must be taken into account. The detector quantum efficiency decreases by a factor of two when anti-blooming methods are employed, requiring a doubling of the exposure time. Also, resolution is lowered, as there are more gaps between pixels.

To counteract blooming, stacked shorter time exposures create the effect of a longer exposure without blooming. More processing would be required, but more accurate results are produced.

4.5 Dark Current

Dark current is a noise function created from thermal induced charges. Lower dark counts (number of electrons/pixel/sec) will produce less noise; therefore this characteristic will be favored in selection of a detector.

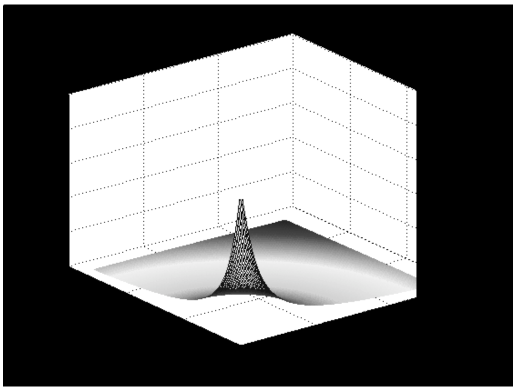

Fig. 2. Computer simulation of detector array image of source directly overhead of the instrument. Proprietary Information, patent protection is being sought.

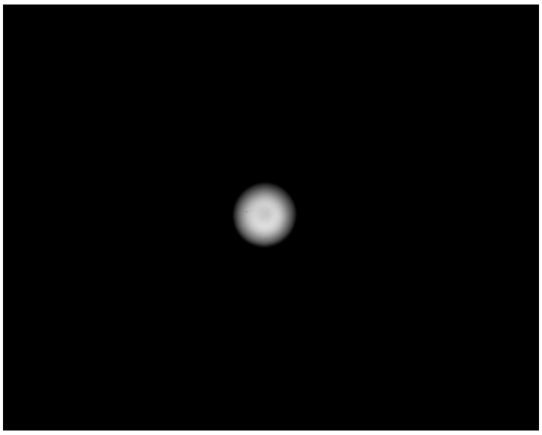

Fig. 3. Actual image of source directly overhead of the prototype instrument obtained in the Ames lab. Proprietary Information, patent protection is being sought.

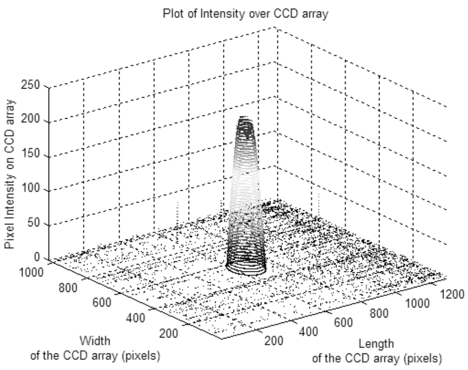

Fig. 4. Contour plot of image in Fig. 8. Proprietary Information, patent protection is being sought.

5. FUTURE WORK

5.1 Instrument Calibration

This function is performed using a simulated light source directed at the instrument. An optical splitter is placed in the path of light to send 10% of the light to a power meter and 90% to the instrument.

The reading on the power meter can be processed to gauge the relative intensity of the simulated light source.

5.2 Data Acquisition Code (DAC)

The direct data collected from detector array needs to be processed and disseminated. The following sections list the necessary components of the code.

5.2.1 Instrument Function

This is a measure of array intensity for the reflected and non-reflected portions of the received signals. Incoming radiation is received by the array either directly through the small end of the imaging optic opening or from the mirror surface. In order to discriminate between the two, a deciphering algorithm must be created.

5.3 Code Products

5.3.1 Area of Direct Beam

Based upon the previously analyzed data, the DAC will determine the area of the direct beam based upon selected threshold intensity.

5.3.2 Centroid of Direct Beam

Given that the shape of the beam will generally be elliptical in nature, an algorithm for the centroid determination will be coded [1].

5.3.3 Intensity of Direct Beam – Interpolation of Diffuse

Given the above two data products, a third one, based upon the intensity of the direct beam can be derived. To establish direct beam intensity, the diffuse beam must be identified and interpolated over the direct beam region. Using the interpolation, the diffuse beam is separated from the direct.

5.3.4 Data versus Program comparison

The product of the code provides a comparison with the SCDS software for a true side-by-side comparison of results and theoretical output. It should be noted that the direct/diffuse from the DAC would be compared to the SCDS output.

6. REFERENCES

1. Martin L.J., and Zurek R.W., An Analysis of the History of Dust Activity on Mars, *J. Geophys*. Res., 98, E2, 3221-3246, 1993.
2. Murphy J.R., Haberle R.M., Toon O.B., Pollack J.B., Martian Global Dust Storms: Symetric Numerical Simulations Including Size-Dependent Particle Transport, *J. Geophy*. Res.,98, E2, 3197-3220, 1993.
3. Santee, M. and Crisp D., Thermal Structure and Dust Loading of the Martian Atmosphere During Late Southern Summer: Mariner 9 Revisited, *J. Geophy*. Res., 98, E2, 3261-3279, 1993.
4. Haberle, R.M., Pollack J. B., Barnes J.R., Zurek R.W., Leovy C.B., Murphy J.R., Lee H., and Schaeffer J., Mars Atmospheric Dynamics as Simulated by the NASA Ames General Circulation Model, 1 The Zonal-Mean Circulation, *J. Geophy*. Res., 98, E2, 1993.
5. Lemmon, M. T. et al. Atmospheric Imaging Results from the Mars Exploration Rovers: Spirit and Opportunity, *Science*, Vol. 306, pp. 1753-1756, 2004.
6. Smith, M.D., Pearl J., and Conrath B., Mars Global Surveyor Thermal Emission Spectrometer (TES) Observations of Dust Opacity During Aerobraking and Science Phasing, *J. Geophys*. Res., 105, E4, 9539-9552, 2000.
7. Bell, J.F. et al, Mars Exploration Rover Athena Panoramic Camera (Pamcam) investigation, *J. Geo. Res.*, 108 (E12), doi:10.1029/2003JE002070, 2003.
8. Maki, J.N. et al. Mars Exploration Rover Engineering Cameras, *J. Geo. Res.*, 108 (E12), doi:10.1029/2003JE002077, 2003.
9. Voltz, F.E., Photometer mit Selen-Photoelement zur spektralen messung der Sonnenstrahlung und zur Bestimmung der Wellenlangenabhangigkeit der Dunstrubung, *Arch. Meteorol. Deophys. Bioklimatol*, B10, 100-131, 1959.
10. WMO, *Recent progress in sun photometry. Determination of aerosol optical depth*, Environmental Pollution Monitoring and Research Program, World Meteorological Organization, Geneva, 1986.
11. Russell, P., Scribner E., and Uthe E.E., *An automated multi-wavelength sunphotometer to characterize transient aerosol and water vapor events, in Third Conf. Atmospheric Radiation*, Amer. Meteor. Soc., Davis, 1978.
12. Tomasi, C., Prodi F., Sentimenti M., and Cesari G., Multi-wavelength sun-photometer for accurate measurement of atmospheric extinction in the visible and near IR spectral range, *App. Optics*, 22 (15), 622-630, 1983.
13. Matsumoto, T., Russell P., Mina C., and van Ark W., Airborne Tracking Sunphotometer, *J. Atmos. and Oceanic Tech.*, 4, 336-339, 1987.
14. Harrison, L., Michalsky J., and Berndt J., Automated multi-filter rotating shadow-band radiometer: an instrument for optical depth and radiation measurements, *App. Optics*, 33 (22), 5118, 1994.
15. Valero, F.P.J., T.P. Ackerman, and W.J.Y. Gore, The effects of the Arctic haze as determined from airborne radiometric measurements during AGASP II, *J. Atmos. Chem.*, 1989 (9), 1989.
16. Kiedron, P., Michalsky J., Schmid B., Slater D., Berndt J., Harrison L., Racette P., Westwater E., and Han Y., A robust retrieval of water vapor column in dry Arctic conditions using the rotating shadowband spectroradiometer, *J. Geo. Res.*, 106 (D20), 24007-24016, 2001.
17. LeBaron, B.A., and Michalsky J., *Ozone measurement using the Chappuis band in the visible spectral region*, International Radiation Symposium, '88, edited by J. Lenoble, and J.F. Geleyn, pp. 519-522, 1988.
18. Michalsky, J., Harrison L., and Berkheiser W.B., Cosine response characteristics of some radiometric and photometric sensors, *Sol. Energy*, 54, 397-402, 1995.
19. King, M.D., Bryne D.M., Herman B.M., and Reagan J.A., Aerosol size distributions obtained by inversion of spectral optical depth measurements, J. *Atmos. Sci*., 35, 2135-2167, 1978.